MAINTENANCE AND IMPROVEMENT OF SOIL PRODUCTIVITY

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Abstract.--Soils on which loblolly pines (*Pinus taeda* L.) grow vary widely in physical and chemical properties and in their capacity to withstand stresses imposed by short rotations, increased biomass utilization, heavy equipment traffic and intensive site preparation. Early soil site studies showed that soil physical conditions which limited rooting volume reduced tree growth. More recent research shows N and P fertilization increases tree growth on many soils, implicating nutrient limiting factors.

Thus, forestry practices that adversely affect the physical and chemical properties of the rooting zone are likely to decrease soil productivity. Windrowing and erosion, which remove nutrient-rich materials from the soil, have the potential to reduce soil productivity by impacting the soil physical and chemical properties. Nutrient removal rates associated with short rotations and total biomass harvest are greater than can be restored naturally. The great stresses imposed on nutrient-deficient soils by intensive management will require an increase in fertilization or culture of N-fixing plants plus fertilization to maintain productivity. Practices that increase the quantity of organic matter on a site strongly contribute to the desirable soil physical and chemical properties that improve soil productivity.

Additional keywords: *Pinus taeda*, loblolly pine, soil physical properties, soil chemical properties, nutrient cycling, nutrient budget.

High-yield intensive forestry is not a management option in the South--it is a management necessity. Recent projections indicate that demand for southern pine will double from 4 billion ft^3 in 1976 to more than 8 billion ft^3 by 2030 (U.S. Forest Service 1981). Little opportunity to expand the forestland base exists, and most of this increased demand will be obtained by increasing production from existing forestlands.

A characteristic loblolly pine (*Pinus taeda* L.) soil does not exist. Soils supporting loblolly pine range from very poorly drained histisols in the lower Coastal Plain to well-drained ultisols in the Piedmont. These soils vary widely in their capacity to withstand stresses imposed by short rotations, increased biomass utilization, more frequent trafficking of heavy equipment, and intensive site preparation. They also vary in their

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responses to drainage, fertilization, or other cultural practices designed to ameliorate. In this paper, we review some factors limiting loblolly pine productivity and discuss environmental conditions under which certain management practices can improve or impair soil productivity.

SITE QUALITY AND SOIL CHARACTERISTICS

Some of the earliest and most comprehensive field investigations of site quality and soil characteristics were conducted by T. S. Coile and his colleagues in the 1930's. The general conclusion of these researchers was that soil conditions which reduced rooting volume also reduced tree growth (Coile 1952). High subsoil bulk density, poor aeration and seasonally high water table reduce rooting volume, and soil profile variables which reflect these conditions are useful criteria for predicting site index. On an eroded Piedmont site, an increase in depth to the subsoil from 2 to 4 inches raised site index at age 50 from 46 to 68 feet. For Coastal Plain soils, an increase in depth to subsoil from 6 to 12 inches was associated with a 5- to 7-foot increase in site index. An excellent review of soil site reports is given by Carmean (1975).

Although early soil-site studies grouped loblolly pine sites by productive capability, the variation within a group was usually large. Recent studies have attempted to correlate loblolly pine growth within more closely defined units using specific soil properties. For instance, McKee (1977) found that 60 to 74 percent of the variation in site index within the Craven, Wahee and Meggett soil series of the South Carolina Lower Coastal Plain was related to soil chemical and physical properties in the A1 and B2 horizons; however, the variables most closely correlated with site index differed for the three series. In the Craven series, soil pH, exchangeable calcium (Ca) and potassium (K), and total nitrogen (N) in the A1 were all significantly correlated with site index as was exchangeable Ca in the B2. In the Meggett series, site index increased with percentage sand in the A1 and B2, and pH in the B2.

Forest fertilization research indicates that most loblolly pine stands respond to N fertilization and many Lower Coastal Plain soils are phosphorus (P) deficient. Fertilization has been treated well in another part of this symposium, and it is mentioned here only to illustrate the role of nutrients in maintaining soil productivity. A decrease in the amount of an element already deficient in a soil is expected to have an immediate effect on soil productivity.

EFFECTS OF MANAGEMENT PRACTICES ON SOIL PROPERTIES

Topsoil Removal and Loss

Despite the abundance of data relating tree growth to surface soil depth, methods of site preparation which remove topsoil are common. Removal of topsoil during improper root-raking or blading reduces soil productivity by removing part of the rooting zone and a disproportionally large amount of nutrients. However, in many soils the decrease in quantity and quality of soil for roots may have a greater impact on productivity than loss of nutrients.

During root-raking and blading operations, tree roots, forest floor and topsoil high in organic matter and nutrients are concentrated into windrows, leaving between windrows a soil with a reduced rooting zone less capable of intercepting and holding water and nutrients for tree growth. Glass (1976) found that root-raking displaced the forest floor and about 2 inches of topsoil from a pine forest in the North Carolina Piedmont. This soil displacement lowered the estimated site index (age 50) for loblolly pine from 79 feet to 65 feet in comparison with an adjoining broadcast burn site. At age 20, the broadcast burn area had 11 more cords per acre in trees 4 inches in diameter and larger than did the windrowed site.

Erosion typically removes fine organic particles and topsoil, but it is difficult to measure erosion and to evaluate its effect on tree growth. Yoho (1980) summarized reported values for erosional losses following various management practices in the southern pine region. Thinning or periodic burning operations resulted in sediment loss of less than 0.1 ton/acre during the first year after treatment. Erosional losses after clearcutting were just over 1 ton/acre during the first year. Losses as high as 6.36 tons/acre were reported following mechanical site preparation. Douglass and Goodwin (1980) measured soil loss in runoff for 3 years after site preparation treatments were applied to 16 small watersheds in the North Carolina Piedmont. Average annual soil loss from areas with 8 to 14 percent slope varied from 0.005 tons/acre for undisturbed forests to 4 tons/acre for KG-bladed and disked watersheds the first year after treatment. Loss from the KG and disked watersheds was just over 3 tons/acre the second year and 2 tons/acre the third year after treatment. The KG-only treatment caused about one-third as much soil loss. A natural debris cover of 50 percent of the soil surface or seeded grass effectively controlled erosion. The authors stated that annual loss of 4 tons/acre of soil exceeds the estimated loss considered acceptable without a decrease in soil productivity.

Soil movement is much greater from mechanical windrowing than from erosion, but the windrowed soil remains on the site and will contribute to total site productivity. Natural mechanisms for dispersing windrowed soil across the site are slow, and total forest production is less. Root-raking and windrowing expose the soil to the impact of raindrops and overland flow, thus increasing the chance for erosion. Therefore, the effects of mechanical soil movement and erosion are often combined on the same site.

Physical Properties

Soil bulk density and soil strength are altered when equipment is used to harvest timber and prepare sites for regeneration. Increases in bulk density decrease soil air space and infiltration rate. The area disturbed in harvesting has been estimated at 33 percent by Hatchell, Ralston, and

and Foil (1970) and 23 percent by Campbell, Willis and May (1973). Site preparation practices such as shearing, piling, root-raking and bedding also require heavy equipment capable of altering the soil's physical properties over the entire site.

Hatchell, Ralston and Foil (1970) studied compaction at 47 locations in the Lower Coastal Plain of South Carolina and Virginia and found that wheel and crawler tractor traffic caused a very sharp increase in bulk density of surface soils after one or two trips and a more gradual increase in density as the number of trips increased. Many locations were compacted to a noncapillary porosity below 10 percent, a level critical for soil aeration and root growth. Compaction caused a greater reduction in noncapillary porosity in wet soils than in dry soils, with puddling being a major contributing factor. Three-year-old seedlings collected from skid trails and a logging area had one-third to one-half the oven-dry weight of seedlings on undisturbed soil. Soil investigations indicated poor aeration may have been the primary limiting factor, but growth was also affected by mechanical resistance to root extension.

Similar results have been reported for a Lower Coastal Plain site in North Carolina by Gent, Ballard, and Hassan (in press). These investigations found that bulk density (g/cm^3) of the surface 3 inches of soil was increased from less than 1.1 in preharvest loblolly pine stands to 1.2 in nonskid trail portions of cut-over areas. Skid trail bulk density averaged 1.4, a value high enough to mechanically impair tree growth in these soils (Mitchell et al. 1981). Aeration porosity was reduced from 25+ percent in the stand before harvest to 11 percent and 13 percent in areas harvested by stemwood and complete-tree methods, respectively. Aeration porosity was less than 10 percent in skid trails. At these low porosities, oxygen diffusion is limited and anaerobic conditions which restrict root growth develop.

Hatchell, Ralston, and Foil (1970) estimated it would take 18 years for bulk density of soil in primary skid trails and log decks to return to the density of undisturbed soils. Productivity of compacted soil can be partially restored by well-timed disking, bedding and fertilization (Hatchell 1981). Disking or bedding is most effective when the soil is slightly moist and friable. Fertilization does not directly improve compacted conditions but increases nutrient availability in the limited area that roots penetrate. It accelerates root development and may speed natural ameliorative processes.

Soil Microclimate

Harvesting and site preparation disturb the relatively stable microclimate which exists beneath the forest floor of an undisturbed forest. Most of these changes are ephemeral and do not directly influence long-term site productivity; however, they exert short-term influences on seedling survival and biologically mediated mineralization processes may affect soil productivity.

Removal of transpiring vegetation during harvest results in an overall increase in soil moisture and an associated rise in water table. This water table rise can approach 6 ft following clearcut harvesting of loblolly pine in poorly drained areas of the Lower Coastal Plain (Trousdell and Hoover 1955). On very poorly drained, fine-textured soils, extensive swamping can occur and trees cannot be reestablished without bedding or drainage.

Schultz (1976) reported that maximum temperature increased and minimum temperature decreased with increasing intensity of site preparation in the coastal flatwoods of Florida. In June, 1 year after site preparation, maximum temperature at 1 inch below the soil surface averaged 51°C in a bedded area, 42°C on a disked site, 38°C on a burned site and 37°C under a longleaf stand. After growth of ground vegetation the second year after treatments, the greatest difference among the sites was only about 3°C. Increases in temperature may increase nutrient availability, thus improving tree growth or in some soils increase biological processes to the extent that excess soluble nutrients leach from the root zone.

Soil Nutrients

Most soils supporting loblolly pine are acid and infertile by crop production standards. For production of corn or soybeans on similar soils several tons per acre of limestone must be applied regularly, and annual treatment with N, P, and K is an accepted practice. In the Lower Coastal Plain, the amount of P considered adequate for crops is three or four times that needed for loblolly pine. The annual application of N and P for crop production may equal the amount applied to loblolly pine for 15 years or a rotation.

These low levels of nutrients in the soil and low fertilization rates needed for loblolly pine indicate the high nutrient efficiency of the loblolly pine system. It also illustrates a delicate balance that may be disrupted by practices that demand more than the soil can provide. Unlike farmers who apply fertilizers liberally to maintain or increase production, foresters generally seek to maintain soil productivity without or with minimum fertilization. Since it is not possible to obtain greater production without removing more nutrients from the system, it is necessary either to develop and select nutrient conserving practices in order to obtain the greatest production from a limited nutrient supply or to increase soil nutrients by fertilization.

Soil Test Analyses and Nutrient Supply.

Site preparation treatments usually do not affect results of analyses for total N and acid extractable soil nutrient concentrations. Burger (1979) compared extractable P, K, Ca and magnesium (Mg) concentrations in the surface 8 inches of a Florida flatwoods site after three treatments: no harvest; clearcutting, chopping and burning; and clearcutting, burning, blading and harrowing. Statistically significant increases in Ca and Mg concentrations occurred in the clearcut, chopped and burned area, but P and K concentrations were unchanged. In a similar study, Morris and Pritchett (1982) were unable to detect any statistically significant differences in extractable nutrient contents resulting from site preparation practices. These tests for extractable nutrient concentrations in the soil should not be relied upon to show nutrient supplying capacity of the rooting zone.

Nutrient Availability

Only a very small part of the annual nutrient requirements for N and P is soluble or available at the beginning of the growing season or any other given time. Continued growth during the season is dependent upon transformation of unavailable forms of the elements to forms that are soluble and can be adsorbed by roots. The same availability processes are responsible for plant growth and nutrient losses by leaching. The large unavailable sources of nutrients and their interactions with moisture and temperature largely control nutrient availability and soil productivity. These complex chemical and biological processes have not been quantified for the mixture of nutrient sources in the soil. Therefore, availability or extractable nutrient tests are used to roughly approximate soil fertility. Relationships between available or extractable and total nutrient contents are frequently discussed, but seldom quantified. There is little value to a large total supply if it is not available to plants, and trees will not thrive if a high current rate of availability cannot be sustained.

A forest system may be divided into three major components--mineral soil, vegetation and forest floor--each of which may be further divided into smaller components or pools. With information on nutrient quantities in each pool at various times, flow models can be developed to show the quantity of an element in each pool and the transfer rates of elements among pools. Assuming that pool sizes and transfer rates regulate nutrient availability and thus control growth, the effect of various practices on nutrient availability and tree growth can be predicted.

NUTRIENT BUDGETS

Some insight into soil productivity can be gained by a budget approach in combination with general knowledge of nutrient availability (table 1). With data on fertilizer responses in existing systems, we are in a fairly strong position to predict the effect of practices that influence nutrients presently limiting growth.

The nutrient budget principle, despite recognized limitations, provides a way to compare the effects of alternate forestry practices on the system's nutrient supplies. Nutrient removal during biomass harvest is unavoidable; however, the quantities removed over a given period of time will vary and are dependent upon management strategy. For instance,

Table 1.--Effects of stem and whole-tree harvest at age 16 or 32 years and various site preparation practices on N demands (Wells and Jorgensen 1977)[a]

Practice or Process	16 Years Whole tree	16 Years Stem	32 Years Whole tree	32 Years Stem
	Demands of N lb/acre			
Harvest	230	103	382	208
KG and windrow	209	336	209	336
Erosion (KG & disk) Piedmont	28	28	28	28
Erosion (chopped) Piedmont	5	5	5	5
Prescribed burning	60	60	120	120
Slash burning	0	120	0	136
Leaching (disking or bedding)	32	32	40	40
Leaching (chopping or herbicides)	16	16	20	20
	Input of N lb/acre			
Nitrogen fixation no seeding	32	32	46	46
Nitrogen fixation seeded legumes	400	400	400	400
Atmospheric deposition	77	77	154	154
Fertilizer	150	150	300	300

[a]Refer to the text for further references and explanations of estimations.

employing three 20-year rotations rather than a single 60-year rotation increases estimated yield of stem from 87 to 144 tons/acre (Switzer, Nelson and Hinesley 1978). This additional yield increases annual nutrient removal. If branches and needles are harvested, the nutrient removal of combined short rotation and total aboveground harvest results in an increase in N removal from 155 to 635 lb/acre and P removal from 12 to 59 lb/acre during 60 years. On a highly productive site, Wells and Jorgensen (1977) estimated a removal of 230 and 103 lb/acre of N for complete and stem harvest at age 16, and at age 32 a corresponding removal of 382 and 208 lb/acre.

Another major form of nutrient removal that must be considered in a nutrient budget is the nutrient loss from the site by soil movement and leaching that mostly occurs during the harvesting and regenerating phases of the rotation. Morris, Pritchett, and Swindel (In press) reported that KG-blading and windrowing following a slash pine clearcut moved 335, 16, and 24 lb/acre, respectively, of N, P and K from between the windrows. This compares well with other work in Florida which showed that site total N reserve was 426 lb/acre less on a windrowed site than on an adjacent chopped site (Burger 1979). Work in progress on the North Carolina productivity studies indicates somewhat smaller movement of nutrients to windrows through rootraking. Windrowing may be executed so that only woody material and a small amount of soil are displaced. Frequently, however, the forest floor and a large amount of mineral soil are moved with the slash, thus degrading soil productivity through nutrient removal in addition to causing damage to the soil's physical properties and baring the soil to erosion.

Nutrient removal in erosion may be estimated from sediment data. In the data of Douglass and Goodwin (1980), erosion was 14,000 lb/acre over 3 years on a KG-bladed and disked watershed. With an estimated N concentration between 0.1 and 0.2 percent, there would be a loss of 14 to 28 lb/acre, not a large amount. Nitrogen loss may be much greater with severe erosion, because the fine materials which erode first are higher in nutrients and organic matter than in soil remaining on the site.

Leaching of nutrients from loblolly pine forests is generally low in comparison with that of most other forests, but such losses may be important on some soils. Calculations based on concentrations in runoff and ground water indicate whether losses in solution are likely to be important. Assuming 10 inches of stormflow (Douglass and Goodwin 1980) and 10 inches of ground-water flow with a nitrate-N concentration of one part per million, nitrogen loss would be 5 lb/acre. Early results from North Carolina soil productivity studies indicate that the concentration of soluble N in the soil water will average two to three parts per million during 3 years of harvesting and regeneration of Coastal Plain and Piedmont loblolly pine and less than 0.1 part per million on undisturbed plots of the same stands. These estimates of solution N losses amount to 30 to 50 lb/acre for a 30-year rotation, which is about 20 percent of input by precipitation. Losses of P in solution are influenced less by site disturbance than are those of N because solubility of P in the soil is low.

Burning of forest materials volatilizes some N; thus, a prescribed burn is expected to decrease N in the forest system in amounts varying from 20 to 100 lb/acre (Kodama and Van Lear 1980, Wells 1971). Volatilization of N by periodic prescribed burning of a mature loblolly pine stand in the Coastal Plain was estimated to be approximately 100 lb/acre (Wells 1971). Although plots had been burned at 3- to 5-year intervals for 20 years, N in the mineral soil to a 4-inch depth plus the forest floor was not significantly different among unburned and burned plots. The much greater understory vegetation on the unburned plots contained considerable N, but it was less than the losses due to 4 or 5 burns during the 20 years. More biological N fixation was found on some burned plots than on unburned plots (Jorgensen and Wells 1971); however, estimated fixation was not sufficient to replenish losses by volatilization. Additional information on the N cycle is needed before the true effects of fire can be determined.

The use of fire at intervals to prepare for regeneration caused no significant changes in nutrients of stream water in the Piedmont (Douglass and Van Lear, In press) and the Coastal Plain (Richter, Ralston, and Harms 1981).

Since slash burns in preparation for planting are hotter than prescribed burns under existing stands, they volatilize greater quantities of nutrients and leave more ash that is subject to movement by wind or water. After stem harvest, a loblolly pine stand may have forest floor and slash residue containing 400 to 500 lb/acre of N, 40 lb/acre of P, and varying amounts of other essential elements. Flinn et al. (1979) reported a loss of 72 percent of the N and 27 percent of the P where logging residue and forest floor were burned after clearcutting a Pinus radiata stand. With similar burning intensity, losses from a loblolly pine clearcut would be about 250 lb/N and 10 lb/P per acre.

Nutrient Replenishment

Nutrients removed or lost during harvest and plantation establishment can be at least partially replenished by atmosphere inputs, mineralogical weathering, and, in the case of N, biological fixation. On balance, these naturally occurring inputs equal or exceed removals in a stemwood harvest on a pulpwood rotation (table 1). Accelerated nutrient export--such as that associated with more complete biomass utilization, site preparation which dislocates topsoil or increases erosion, or severe fires--can create a negative nutrient balance (table 2).

Table 2.--System N change by selected combinations of practices in relation to rotation length and biomass removal

Practices	Rotation	Annual
	-------lb/acre-----	
16 yr Complete, KG windrow, Disk, Prescribed burn	-478	-30
16 yr Complete, KG windrow, Disk, Prescribed burn, Legumes	-78	-5
32 yr Complete, KG windrow, Disk, Prescribed burn	-591	-18
32 yr Complete, KG windrow, Disk, Prescribed burn, Legumes	-191	-6
16 yr Stem, Chopped	-19	-1
16 yr Stem, Chopped, Slash burn, Legumes	+261	+16
32 yr Complete, Prescribed burn, Chopped, Legumes	+41	+1
32 yr Stem, Prescribed burn, Herbicide, Natural regeneration	+149	+5

Fertilization can add nutrients in quantities equivalent to net exports; but they may not be as efficiently utilized as naturally occurring nutrients. Nitrogen fertilization offers the greatest opportunity for improving tree nutrition and tree growth, but its short-term effectiveness of 5 to 7 years is not accepted as a general improvement in soil productivity. Results from long-term studies may show that N fertilization, like P fertilization, has long-term effects upon the soil.

Soil total N and plant available N can be improved by seeding N-fixing plants when trees are planted (Jorgensen 1981). Preliminary results indicate 300 to 500 lb/acre of N can be added to the system over a 4- or 5-year period, resulting in improved tree growth. Nitrogen from biological N fixation is mostly in an organic form, hence, available over a longer term than fertilizer forms.

Harvesting and KG + windrow practices are the most demanding of system nutrients followed by burning and leaching which are approximately one half as demanding. The culture of N-fixing plants and fertilization are the greatest opportunities for replenishing N in the system. Both of these practices are thoroughly discussed in this symposium. As shown in table 2, combinations of complete tree harvest and intensive site preparation as often practiced on highly productive sites are demanding beyond normal input levels. With methods to enhance N fixation and/or fertilization, these larger demands can be balanced and with low demanding practices of less intensive site preparation and stem harvest these ameliorative practices can increase total N in the system

Units of N added as fertilizer and removed from the site by harvest and during regeneration are not of equal value to soil productivity. The N lost in erosion, windrowing, burning and harvesting is mostly in the organic forms which would normally be mineralized over many years. Organic matter and organic N are essential to maintaining the physical, chemical and biological properties of the soil; therefore, fertilization is not a viable substitute for N losses on many infertile soils already low in organic matter.

On the basis of known deficiencies and losses from the system, the potential for impact of management practices on soil fertility are in order of N > P > K > Ca > other elements. Like N, P and K demands on the soil-forest system exceed the input for a number of management practice combinations. Phosphorus deficiency, although severe on many lower Coastal Plain sites, is less difficult to correct than is N. Rock phosphate, a slowly soluble source of P, is cost effective and persistent in the soil. With large amounts of biomass removal and accelerated leaching, K and Ca will become limiting to growth on more soils. Potassium is persistent in the system because when available, it is taken up in luxury quantities and cycled rapidly by vegetation. Calcium leaches readily with the nitrate ion and its loss may decrease soil productivity of base deficient sandy soils.

The sum of nutrients in the rooting zone of mineral soil, in the forest floor, and in the roots is considered the site reserve. The ratio of reserve to loss is an indicator of the potential capacity of a soil to sustain the nutrient supply. For soils with N reserve of 2,000 lb/acre in the root zone, the deficit of 600 lb/acre for a rotation (table 2) is no doubt more than the system can tolerate without an immediate decline in soil productivity. For a soil with 10,000 lb/acre of N, a 600 lb/acre change in soil N is far less detrimental. Phosphorus, K, and Ca reserves are often large in relation to system change but availability of these elements varies widely. To provide the required quantity of an element for a large uptake, availability as a percentage of the total must be greater on soils low in reserves; however, the opposite may be the case because the more soluble materials have weathered. At present, foliar analysis and soil testing can be useful techniques for early detection of declining soil productivity in the same way they are useful for prescribing fertilization.

It has been suggested that management practices be tuned to natural processes of nutrient input from the atmosphere and weathering of soil minerals. Although ecologically sound, this approach overlooks the production increases which can be realized by more intensive utilization, site preparation and a program of supplementary fertilization and/or culture of nitrogen-fixing plants.

SUMMARY

Forest soil productivity responds to practices imposed upon the site. The desire to obtain the greatest possible economic returns from forests may at times conflict with biological processes, and a lack of knowledge makes it impossible to accurately evaluate short-term objectives in relation to long-term productivity.

Soil bulk density and aeration are frequently damaged by use of heavy equipment when the soil is wet. Restoration of the soil may require several decades or it may be impossible. Drainage and proper scheduling of equipment operation can prevent much of the damage to soil physical properties.

Removal of forest floor and topsoil to windrows when preparing for planting has a negative influence on soil fertility, tree rooting zone and soil physical properties which results in reduced tree growth. Windrowing should be reevaluated and alternative methods developed in light of its negative effects on soil productivity.

Nutrient removal rates with short rotations and total biomass harvest are greater than natural addition rates. Thus, net declines in N and P are expected to place great stress on nutrient-deficient soils resulting in the need for more fertilization. Fertilization, culture of N-fixing plants, and harvesting intensity in relation to soil properties are management options that can prevent or alleviate nutritional problems.

Organic matter in the mineral soil, forest floor and logging slash is a source of nutrients and plays an important role in maintaining the soil physical properties and preventing erosion. Practices that maintain and improve the quantity of organic matter on the site will produce returns in improved soil productivity.

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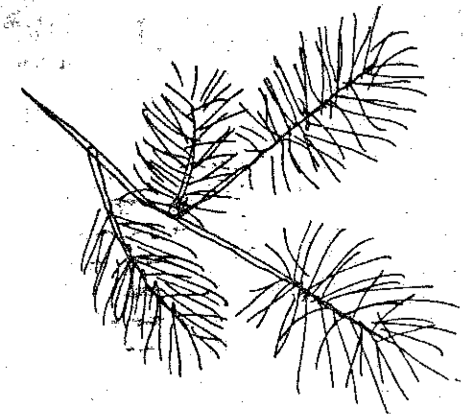

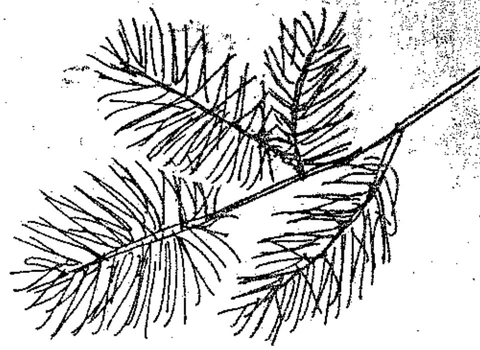

SYMPOSIUM
ON
THE LOBLOLLY PINE ECOSYSTEM
(East Region)

December 8-10, 1982

Raleigh, North Carolina